MODELLING TURBULENT FLAME IGNITION AND BLOWOUT

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A statistical mixing model incorporating an overall rate equation to describe the fuel oxidation process has been developed for studies of ignition and blowout in a combustor primary zone. This zone is treated as a partially stirred reactor whose composition is described by a statistical ensemble of equal mass fluid elements. This ensemble experiences mixing interactions, which represent the turbulent mixing process, at time intervals governed by an empirically determined mixing frequency. Each mixing interaction is computed by randomly selecting two different elements which are then allowed to mix completely so that they reach a mean composition depending on their thermodynamic states prior to mixing. The two elements then separate, and the chemical kinetics proceed depending on their new composition and temperature.

Material flows into and out of the primary zone are simulated by element additions and removals at a rate governed by the residence time of the reactor. The randomness of the flow in the primary zone is simulated by randomly choosing elements to be taken out of the reactor and replacing them with unburnt elements at the inlet conditions.

Imperfect premixing (i.e. the presence of small-scale composition nonuniformities) of the fuel-air mixture flow into the primary zone is accounted for by assuming a Gaussian distribution in the fuel fraction about the mean fuel fraction. The nonuniformity of the inlet mixture is then quantified by defining an unmixedness parameter, s, equal to the coefficient of variation of the distribution. A value of $s = 0$ corresponds to complete premixing; increasing s corresponds to increasingly imperfectly premixed mixtures.

To simulate the ignition process, the ensemble of fluid elements is initialized by assuming that all the elements are unburnt. The spark is replaced by igniting a few elements at time $t = 0$. The ensemble properties (assumed equal to the mean of the properties of the elements) are calculated as a function of time. Non-ignition is characterized by the ensemble burnt fraction, $\overline{B}$, decreasing with time; successful ignition requires a growth in $\overline{B}$. The lean ignition limit is defined as the leanest mixture which can be ignited. To simulate blowout, most (or all) of the elements are assumed fully burnt at $t = 0$ and the ensemble properties are allowed to evolve with time. Blowout is characterized by $\overline{B}$ continuously decreasing with time to approach zero. The lean blowout limit is defined as the richest mixture that blows out.

The procedures outlined above were used to examine the effects of inlet temperature, pressure and velocity, on the lean limits of uniform mixtures. Comparisons were made with available data. The influence of inlet mixture nonuniformity was explored by varying s. The flameholder and combustor modelled for this study are described by Radhakrishnan (1978). The length of the primary zone was assumed equal to the length of the recirculation zone.

The results of the parametric study are as follows. Increases in mixture inlet temperature T_u lead to higher temperature burnt products and hence increased burning rates. Hence, at constant inlet velocity, U, the limits will decrease with T_u: or for constant fuel-air equivalence ratio, ϕ, U at ignition and blowout will increase with T_u. This behavior is displayed by the model predictions. The predicted blowout limits agree well with the experimental data; however, the predicted limits are richer. This is attributed to the different fuels used in the modelling (CH_4) and experimental work (C_3H_8). We predict that neither the lean ignition nor blowout limit has a strong dependence on the pressure. This is consistent with the findings of Bolt and Harrington (1967) and Roffe and Venkatramani (1978a). Increases in U lead to lower residence times and faster mixing rates and hence richer lean limits. The predicted blowout limits again compare favorably with the experimental findings: for reasons given above, the ignition limits are richer.

With increased mixture nonuniformity, the predicted lean ignition limit is leaner. The value of s in a typical combustor primary zone is about 0.5. For this value of s, the model predicts the lean ignition limit to be about 25 percent less than that for the uniform case. Although quantitative comparisons between the model predictions and the experimental data are not possible, our experimental data shows a substantial decrease in the lean limits when the distance over which the fuel and air are allowed to mix is decreased (thereby making the fuel-air mixture less uniform).

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References

Anderson, D.N. (1975); NASA Technical Memorandum, TM X-71592, March 1975.

Anderson, D.N. (1975a); NASA Technical Memorandum, TM X-3301, October 1975.

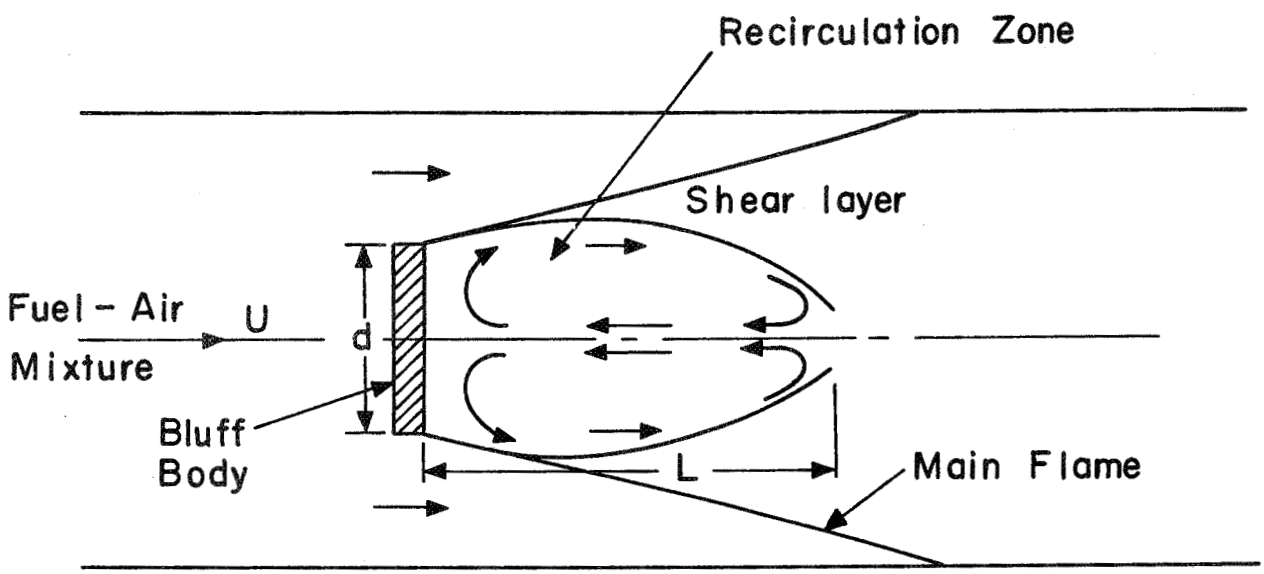
Bolt, J.A. and Harrington, D.L. (1967); SAE Paper 670467.

Marek, C.J. and Papathakos, L.C. (1976); NASA Technical Memorandum TM X-3383.

Radhakrishnan, K. (1978); Ph.D. Thesis, M.I.T.

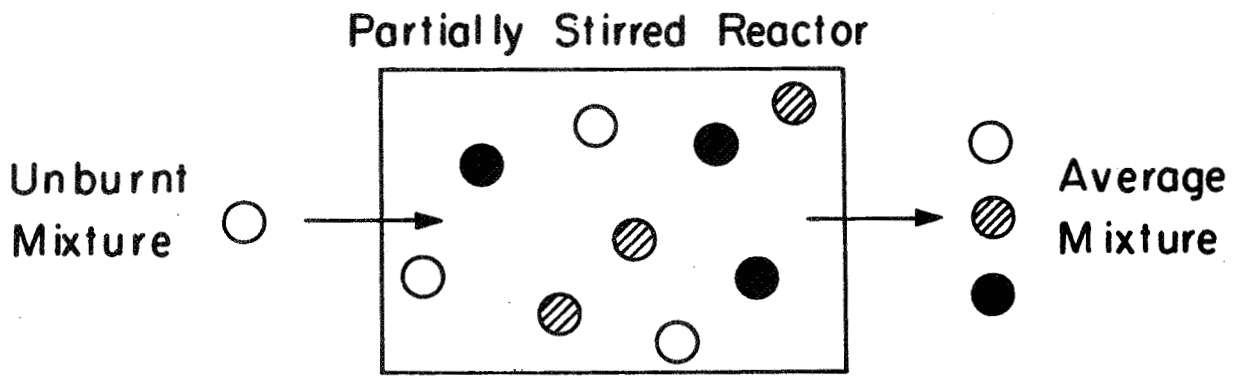
Roffe, G. and Venkatramani, K.S. (1978); NASA Contractor Report CR-135424, June 1978

Roffe, G. and Venkatramani, K.S. (1978a); NASA Contractor Report 3032, July 1978.



Schematic of Bluff Body Stabilized Flame

Simulation of Recirculation Zone



Monte Carlo Mixing Interaction

Element	i	j	i	j
Burnt Fraction	B_i	B_j	$(B_i + B_j)/2$	

Model Parameters And Relations

Mixing Frequency

$$\beta = (P_j/ML^2)^{1/3} = \left(\frac{1}{2}\dot{m}\, U_j^2/ML^2\right)^{1/3}$$

Residence Time

$$\tau_r = (V/\dot{v}) = c\ L/U$$

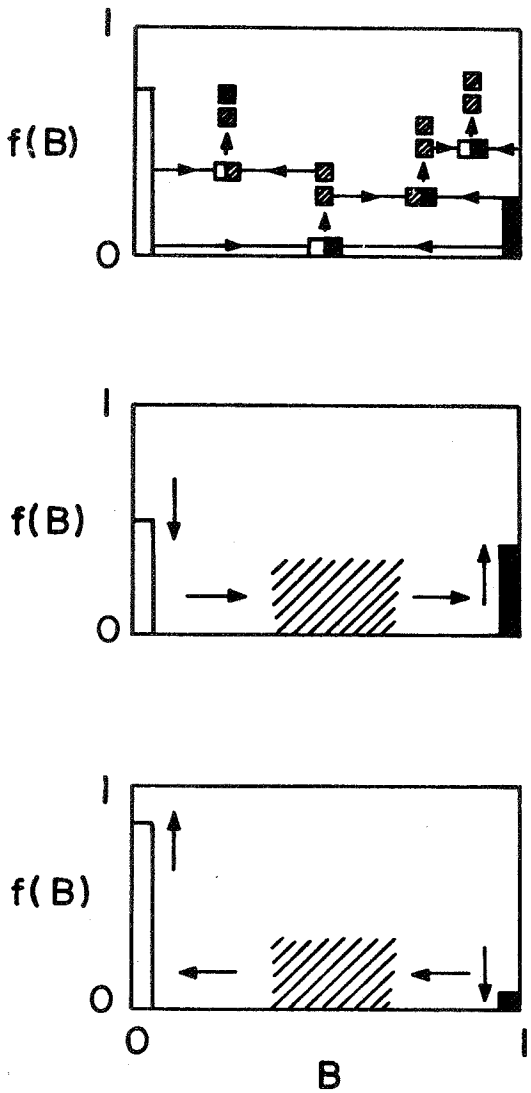
Chemical Kinetics

$$\frac{d}{dt}[CH_4] = -10^{13.2} \exp(-48400/RT)[CH_4]^{0.7}[O_2]^{0.8} \text{ mole/cm}^3\text{s}$$

Ensemble Property

$$\overline{Z} = \frac{1}{N}\sum_{i=1}^{N} Z_i$$

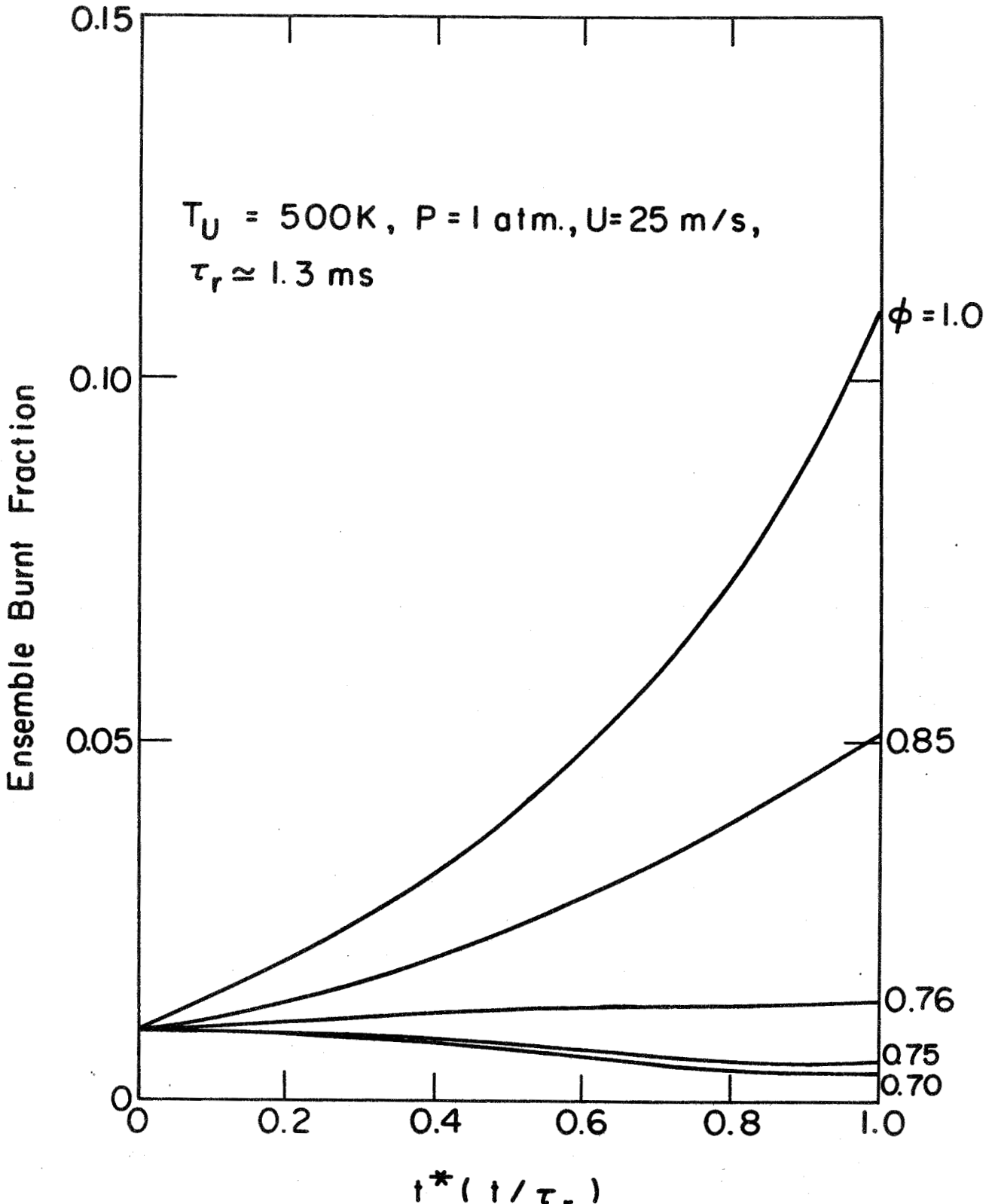
Example : Ignition



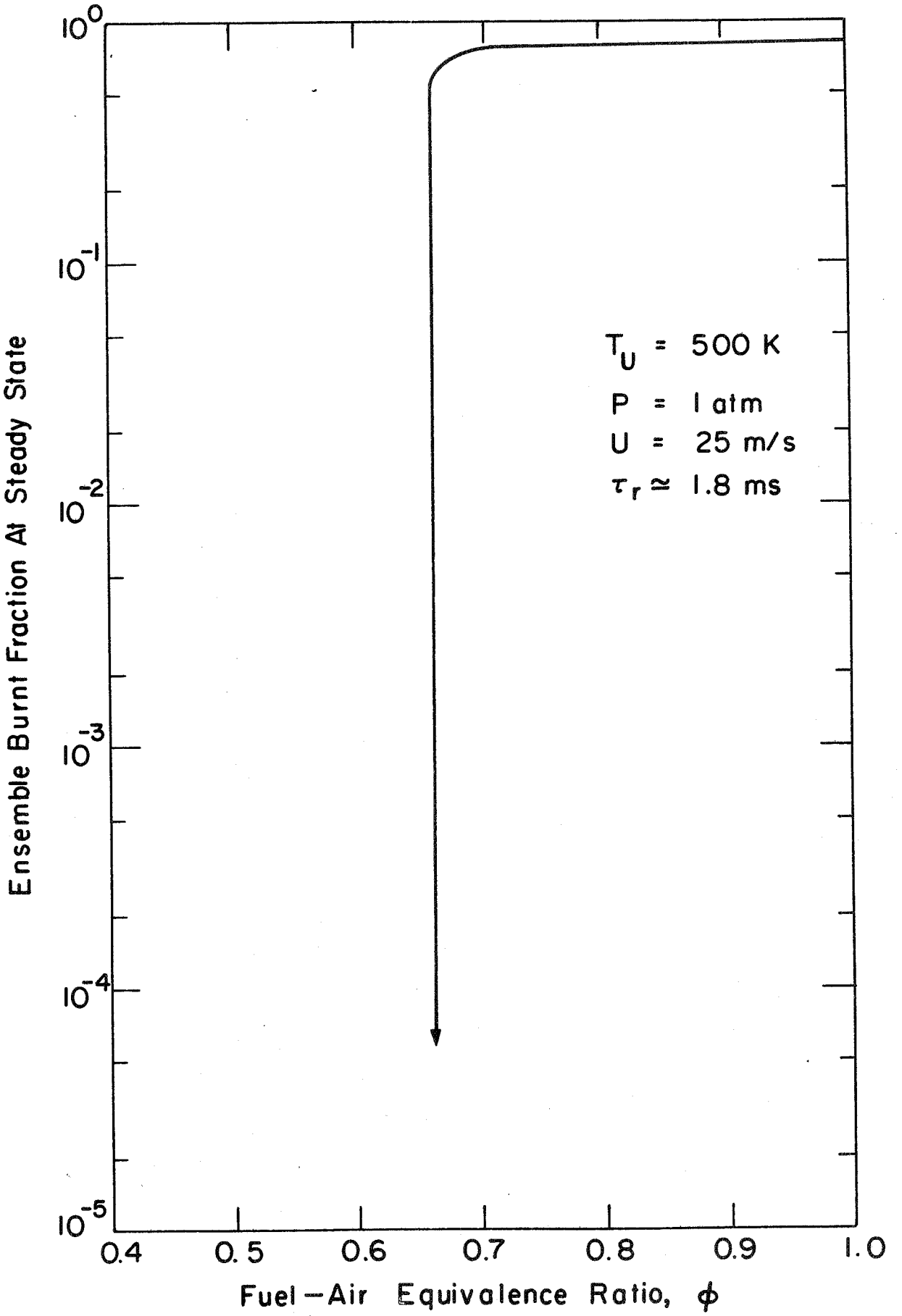
Development of Distribution Function Due to Mixing

Ignition
$\overline{B}$ Increases

No Ignition
$\overline{B}$ Decreases



Example: Lean Ignition Limit



Example: Lean Blowout Limit